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Final Report

Cooperative Agreement NCC 5-11: Altimetry Data over Trenches and Island Arcs and Convection in the Mantle

Dear Ms. Wiseman:

I enclose a report of work performed under the above contract as per your request. This report was recently submitted to Mr. E. Lee Harper and Dr. David Smith of NASA, who are the technical officer and science advisor, respectively, for this contract. The report is listed as a Semi-Annual Status Report because the work is being continued under contract #NAG5-94. Mr Harper has verbally approved the use of the present report as a Final Report for contract NCC5-11.

Sincerely yours,

Glyn Jones

Glyn M. Jones
Principal Investigator NCC5-11

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cc. NSTIF

Altimetry Data over Trenches and Island-Arcs and Convection in the Mantle

Abstract

Transfer function techniques have been developed to calculate the isostatic component of the geoid signal over trench/island-arc/back-arc systems. Removal of this isostatic component from geoid profiles determined by GEOS-3 radar altimetry leaves a residual geoid that can be attributed to the effect of mass inhomogeneities below the depth of compensation. Efforts are underway to extend the analysis to all the major trench/island-arc systems of the world. In conjunction with numerical models of flow and temperature in subduction zones which are also being developed, this work should provide more detailed understanding of the dynamic processes occurring beneath island-arcs.

Altimetry Data over Trenches and Island-Arcs and Convection in the Mantle

Introduction

The nature of the deep structure of subduction zones is one of the major unresolved topics in geodynamics. Such important questions as the nature of deep earthquakes beneath island arcs and the role of the descending lithosphere in driving plate motions will remain enigmatic until a better understanding of the processes operating in subduction zones is achieved.

In the past ten years or so, much effort has been devoted to this question, but progress has been slow. There are good reasons for this. The problem is extremely complex and precise data with which to test possible models have until recently been few.

With the availability of high precision satellite altimetry measurements of the shape of the ocean surface derived from GEOS-3 and SEASAT, however, this situation has now changed. The far more extensive and continuous coverage of the gravity field in the oceans available through satellite altimetry now allows the opportunity to place much tighter constraints on models of flow and temperature in subduction zones than heretofore possible. In conjuction with recent advances in determining the flow law of olivine and also in our understanding of plate kinematics, detailed modeling of the dynamics of subduction zones now appears warranted. This proposal addresses the analysis of GEOS-3 measurements of the shape of ocean surface over trench-island arc systems and

discusses numerical models of flow and temperature in subduction zones that the altimetry data will be used to constrain. The proposed work is based upon the results of previous work funded by NASA under Cooperative Agreement NCC 5-11 "Altimetry Data over Trenches and Island Arcs and Convection in the Mantle". These results are first briefly described and then proposed new work is presented.

Results of work performed to date

One of the reasons for believing that satellite altimetry data offer a potentially important constraint on the deep structure of subduction zones is shown in Figure 1. This figure shows averaged geoid height variations derived from GEOS-3 altimetry over a number of different trench/island-arc/back-arc systems plotted as a function of the inferred age of the back-arc basin. There is obviously a strong inverse correlation between the amplitude of the geoid signal over these regions and the age of the associated back-arc basin. This is emphasized in Figure 2, which displays individual altimetric geoid profiles over the Tonga, Bonin and Western Aleutian arcs.

There appear to be at least two explanations for this correlation:

a) It is a topographic effect due to the shallower depth of young back-arc basins combined with the difference in lithospheric ages on opposite sides of the trench. The generally small free-air gravity anomalies observed over back-arc basins indicate that

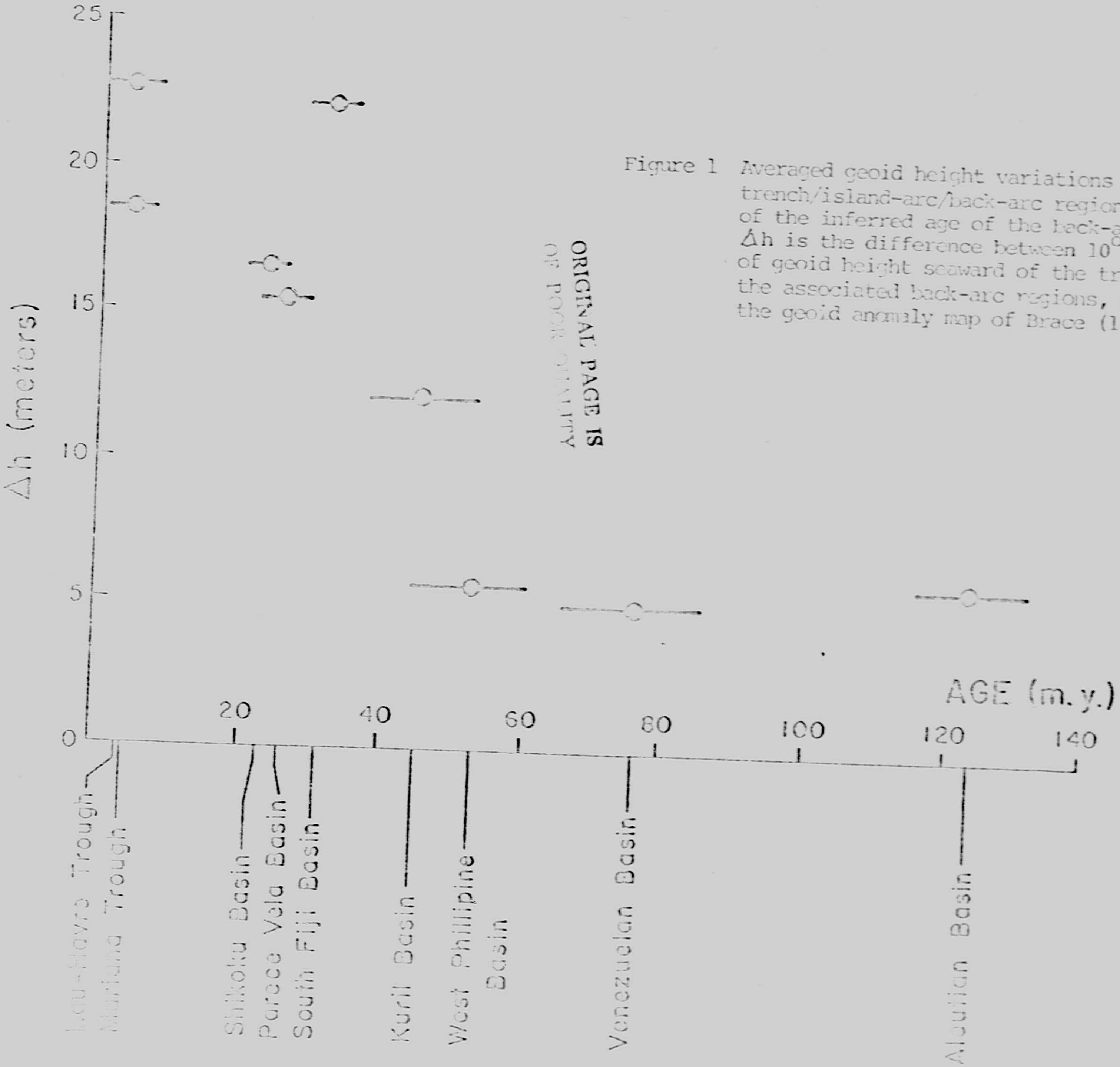

Figure 1 Averaged geoid height variations over various trench/island-arc/back-arc regions as a function of the inferred age of the back-arc basin. Δh is the difference between $10^{\circ} \times 10^{\circ}$ averages of geoid height seaward of the trench and over the associated back-arc regions, estimated from the geoid anomaly map of Brace (1977).

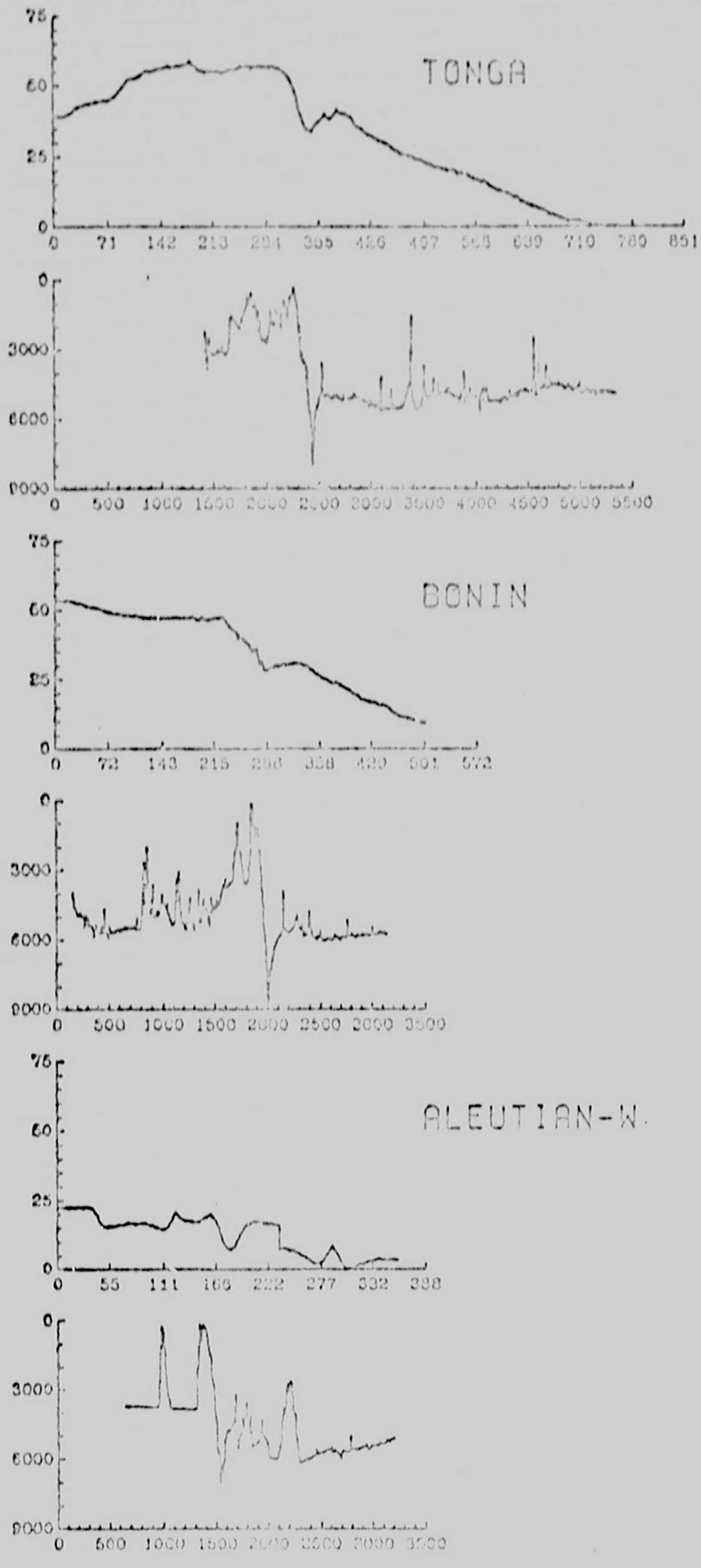

Figure 2 GEOS-3 geoid height profiles over three trench/island-arc systems and associated bathymetry derived from nearby ships' tracks.

these regions are in approximate isostatic equilibrium. Because of the difference in the mean depth of the ocean floor in the back-arc area and seaward of the trench, however, there should be a long-wavelength contribution to the geoid signal over trenches and island-arcs due solely to the topography and its compensation. Since the mean depth of back-arc basins appears to systematically increase with age, this topographic component of the geoid should therefore decrease with the age of the back-arc area.

b) It could reflect differencies in the deep structure of subduction zones related to the presence or absence of an active back-arc region. This is supported by the observation that the inferred dip of the downgoing slab, as reflected in the distribution of intermediate and deep earthquakes, is generally steep beneath regions of active or recent back-arc extension and shallow beneath regions where back-arc extension is absent (Uyeda and Kanamori, 1979).

From the point of view of investigations of the deep structure of subduction zones, possibility (a) is a complicating effect since it results from shallow crustal/upper mantle structure that may mask the gravity effect due to deeper structure.

Transfer function techniques have therefore been developed to calculate the component of the geoid signal over trenches and island-arcs due to effect (a).

The method is illustrated in Figures 3 and 4 and can be described as follows:

Given a function b(x) representing bathymetry, we seek a filter f(x) which, when convolved with b(x), will predict the theoretical geoid variation n(x) due to topography and its compensation, viz.

$$n(x) = \int_{-\infty}^{\infty} b(x')f(|x-x'|)dx' \tag{1}$$

Taking the Fourier transform of both sides of equation (1) we obtain

$$N(S) = B(S)F(S) \tag{2}$$

where N(S) represents the Fourier transform of n(x), etc., and S is the transform variable. We note from (1) that if b(x) is a delta function

$$b(x') = \delta(x')$$

then $n(x) = f(|x|)$. The filter f therefore represents the Green's function response to a point topographic anomaly on the ocean floor. The Fourier transform of this filter is known as the admittance and can be theoretically calculated for different schemes of isostatic compensation. Figure 3a shows the form of the admittance for the Pratt-Hayford model of isostasy in which topographic variations on the ocean-floor are compensated at depth by variations in the density of the mantle. The spatial filter corresponding to Figure 3a is shown in Figure 4.

The method proceeds as follows: The Fourier transform of the observed bathymetry (Figure 3d) is used to obtain the bathymetry spectrum (Figure 3b). This complex spectrum is multiplied by the

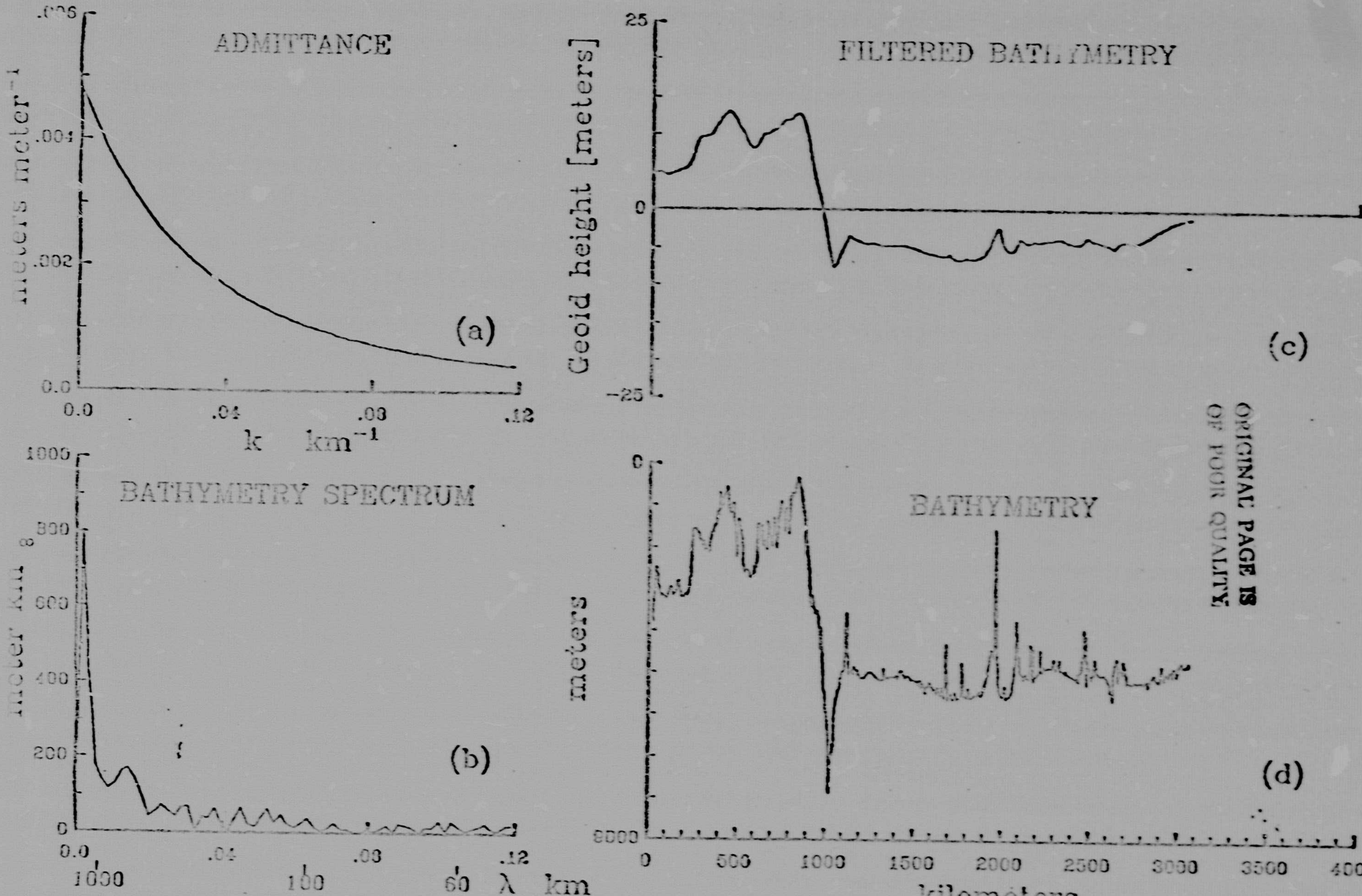

Figure 3 Illustration of the transfer function technique used to predict geoid variations due to ocean floor topography and its compensation. Figure 3a) is the theoretical admittance for the Pratt model of isostasy plotted as a function of the wavenumber k (= $2\pi/\lambda$). The spectrum of the observed bathymetry (Figure 3b) is multiplied by the admittance and the inverse Fourier transform applied to the result. This procedure gives the theoretical isostatic geoid (Figure 3c).

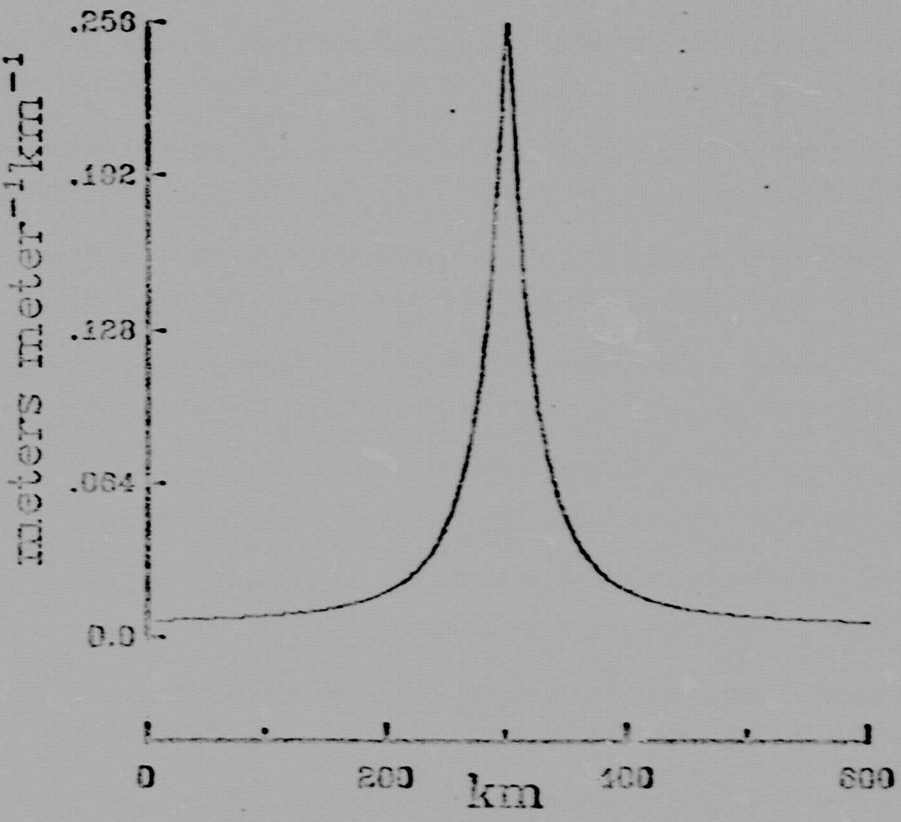

Figure 4 Spatial geoid filter corresponding to the admittance function shown in Figure 3a.

theoretical admittance and the inverse Fourier transform of the result taken to obtain the isostatic component of the geoid (Figure 3c). This procedure is equivalent to convolving the filter in Figure 4 with the observed bathymetry (Figure 3d) but calculations proceed much more rapidly in the wavenumber domain. Care must be taken to avoid spurious results due to edge effects. This was accomplished by extending the left hand end of the profile in Figure 3d by 500km and applying a 500km long cosine taper to both ends before calculating the spectrum.

It can be seen from Figure 3c that 15-20 meters of the observed geoid variation over the Tonga arc can be attributed to the bathymetric effect. Subtraction of this component from the observed geoid gives a residual geoid shown as a dashed line in Figure 5. The residual geoid therefore represents that part of the observed geoid signal that can be attributed to sublithospheric sources.

The filter shown in Figure 4 represents the geoid effect due to a line source assuming a Pratt scheme of isostatic compensation. Other filters can easily be constructed for other isostatic mechanisms, such as the Airy-Heiskanen mechanism, in which topographic variations are compensated by variations in crustal thickness. The question of which mechanism is more appropriate in a particular instance is to some extent subjective but the Pratt model seems to be the most appropriate for island-arcs with evidence of presently active or recent extension behind the arc. These regions are characterized by high heat flow in the back-arc

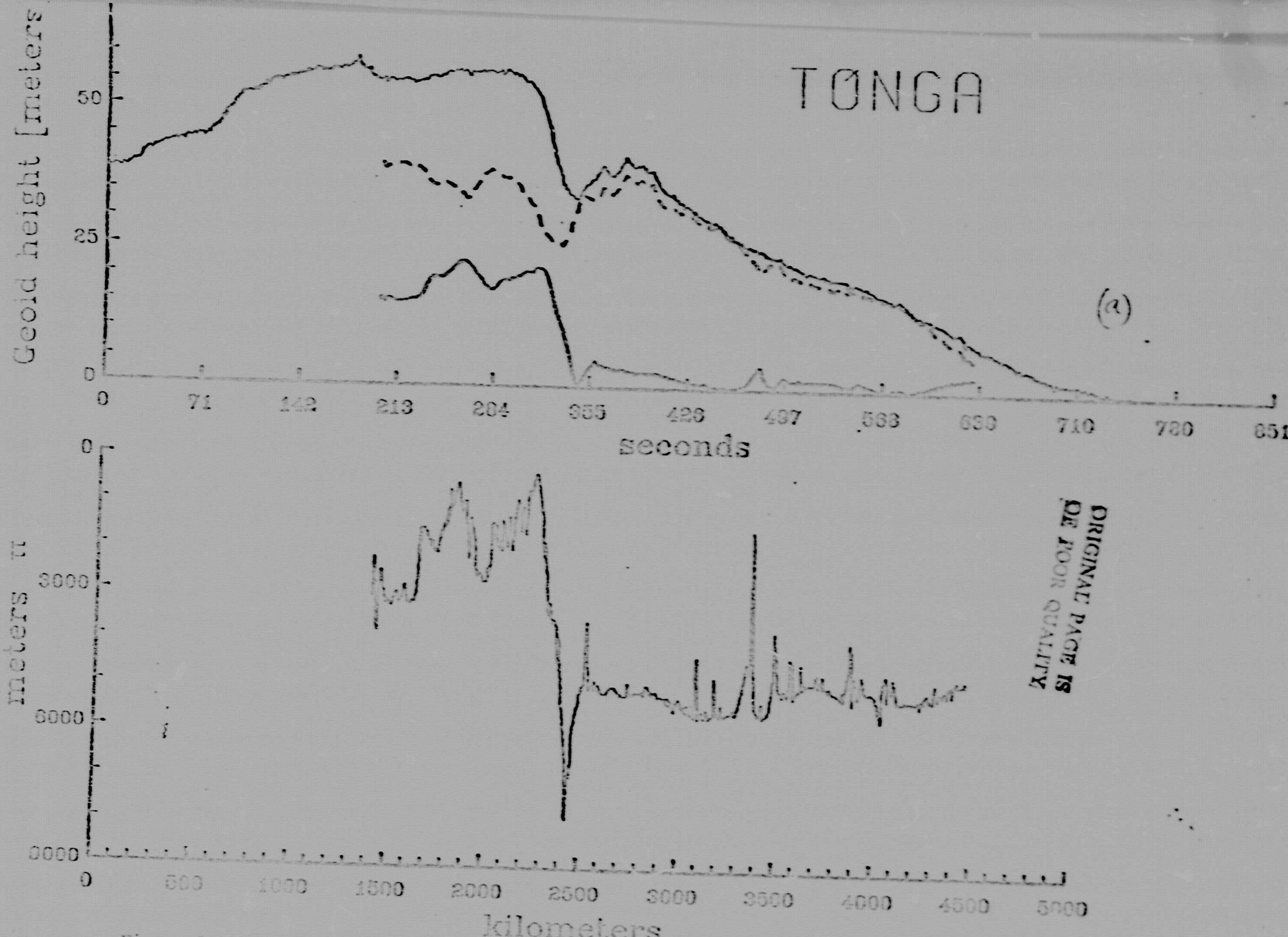

Figure 5 Comparison of observed GEOS-3 geoid (upper solid line in a) with theoretical isostatic geoid (lower solid line in a) resulting from the bathymetry shown in the lower half of the figure. The dashed line is the difference geoid that can be attributed to sub-lithospheric sources. The observed and calculated geoid curves have been shifted to make all geoid values positive.

region and anomalous seismic attenuation behind the downgoing slab, all indicative of anomalous mantle conditions down to some depth. On the other hand, the Airy-Heiskanen model may be more appropriate for older arcs with normal heat flow in the back-arc area.

It can be seen from Figure 5 that subtraction of the isostatic component from the GEOS-3 geoid successfully removes most of the topographic effects except in the region immediately seaward of the trench. The reason for this is that the topography immediately seaward of the trench results, not from isostatic compensation, but from the flexure of the subducting plate as it enters the trench. This outer rise is present seaward of most trenches and can give rise to gravity anomalies of up to 60 milligals (Watts & Talwani, 1974). These anomalies are much larger than those calculated assuming an isostatic model and therefore the computed geoid in this region is too small.

This problem was overcome by applying a separate filter corresponding to a model of a bending plate to the outer rise region seaward of the trench. The results are shown in Figure 6 in which it can be seen that the outer rise component of the observed geoid signal has now been removed resulting in a residual geoid which is smoother than in Figure 5.

The above procedure was also applied to the other profiles shown in Figure 2, with the results shown in Figures 7 and 8. Figure 7 compares the results obtained from profiles crossing the Tonga and Bonin island-arc systems. It is interesting to note that although the observed geoid height variation is larger over

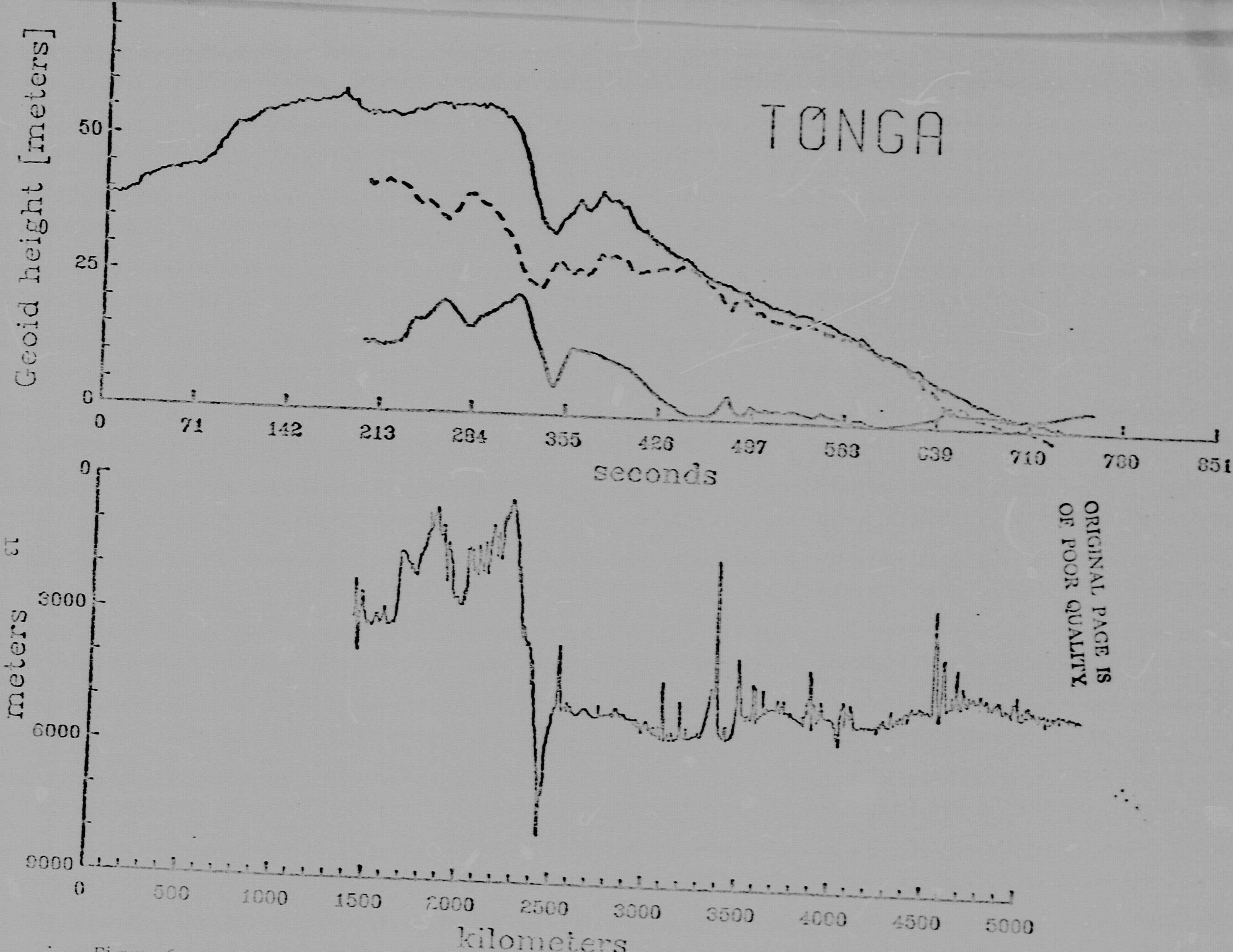

Figure 6 Same as Figure 5 except that a filter corresponding to a bending plate model has been applied to the outer rise region seaward of the trench axis. This removes the outer rise component of the observed geoid signal, leaving a residual geoid that is smoother than in Figure 5.

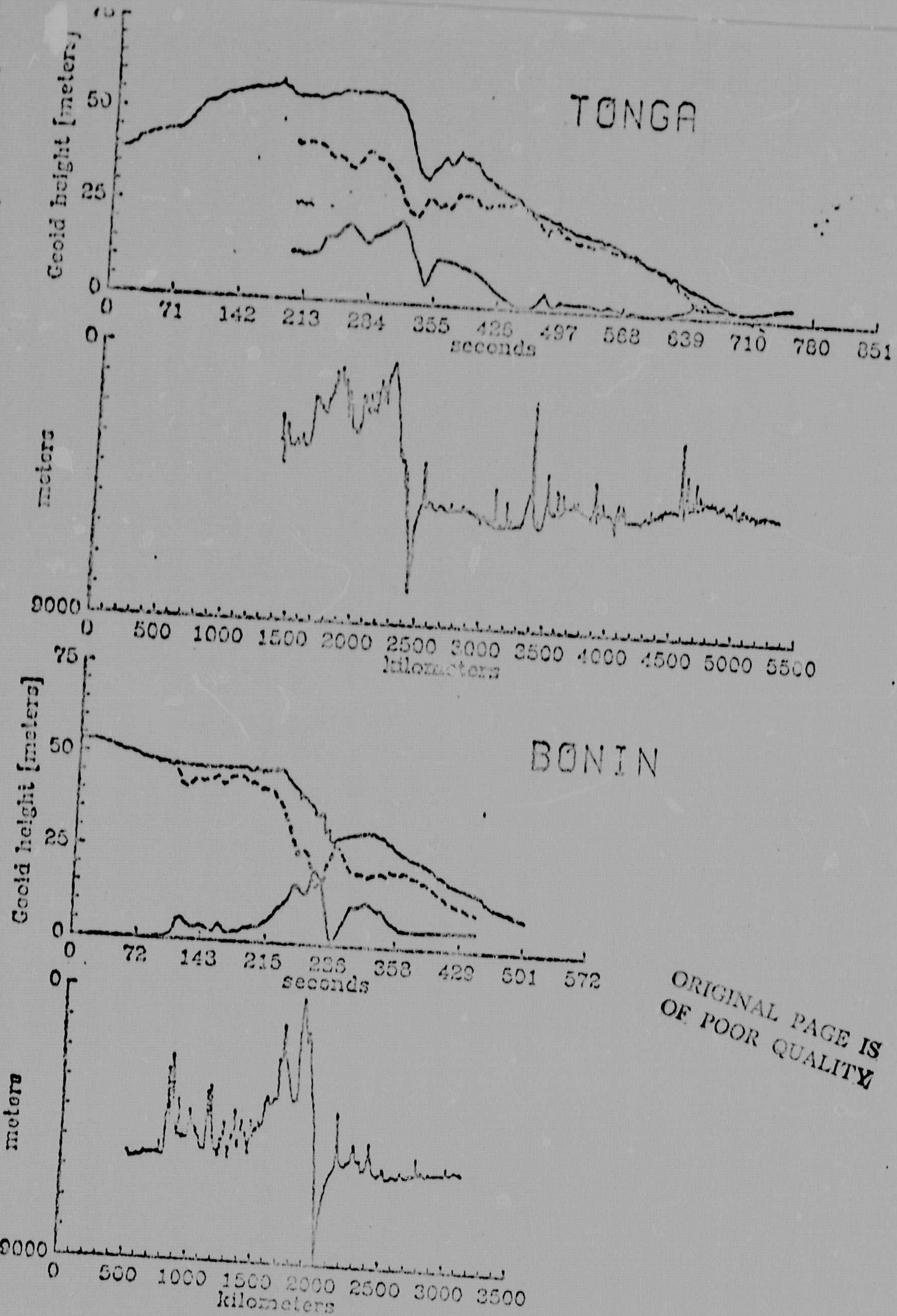

Figure 7 Comparison of results using profiles crossing the Tonga and Bonin arcs. Note that removal of the isostatic geoid component from the observed GEOS-3 data results in residual geoids that are roughly similar in shape and amplitude for the two cases.

the Tonga arc than over the Bonin arc, the residual geoids left after subtracting the isostatic component are roughly similar in shape and amplitude for the two cases. This suggests a similarity in the deep structure beneath these two regions.

Figure 8 displays the results for profiles crossing the Western Aleutian trench. The back-arc area in this region has normal heat flow and there is no evidence of anomalous attenuation in the mantle behind the downgoing slab. In this case, an Airy isostatic model was therefore used to compute the topographic geoid component except over the outer rise where a bending plate model was used as before. There is an offset in the GEOS-3 data along this particular track and it is interesting to note that if this offset were to be removed, the amplitude of the residual geoid variation would be only of the order of 5 meters. The great difference between the amplitudes of the residual geoids in Figures 7 and 8 point to similar differences in the deep structure beneath these regions. Such differences are also suggested by the distribution of earthquakes beneath these areas. In the former case, earthquake foci extend down to 600km whereas in the case of the Aleutian arc, earthquakes deeper than 300km are unknown.

These differences in the maximum depth of earthquakes beneath island arcs have, of course, long been recognized and generally attributed to differences in the thermal structure (e.g. McKenzie, 1969) What is new here is that the geoid data offers an additional important constraint that will allow some of the previous ideas to more critically tested.

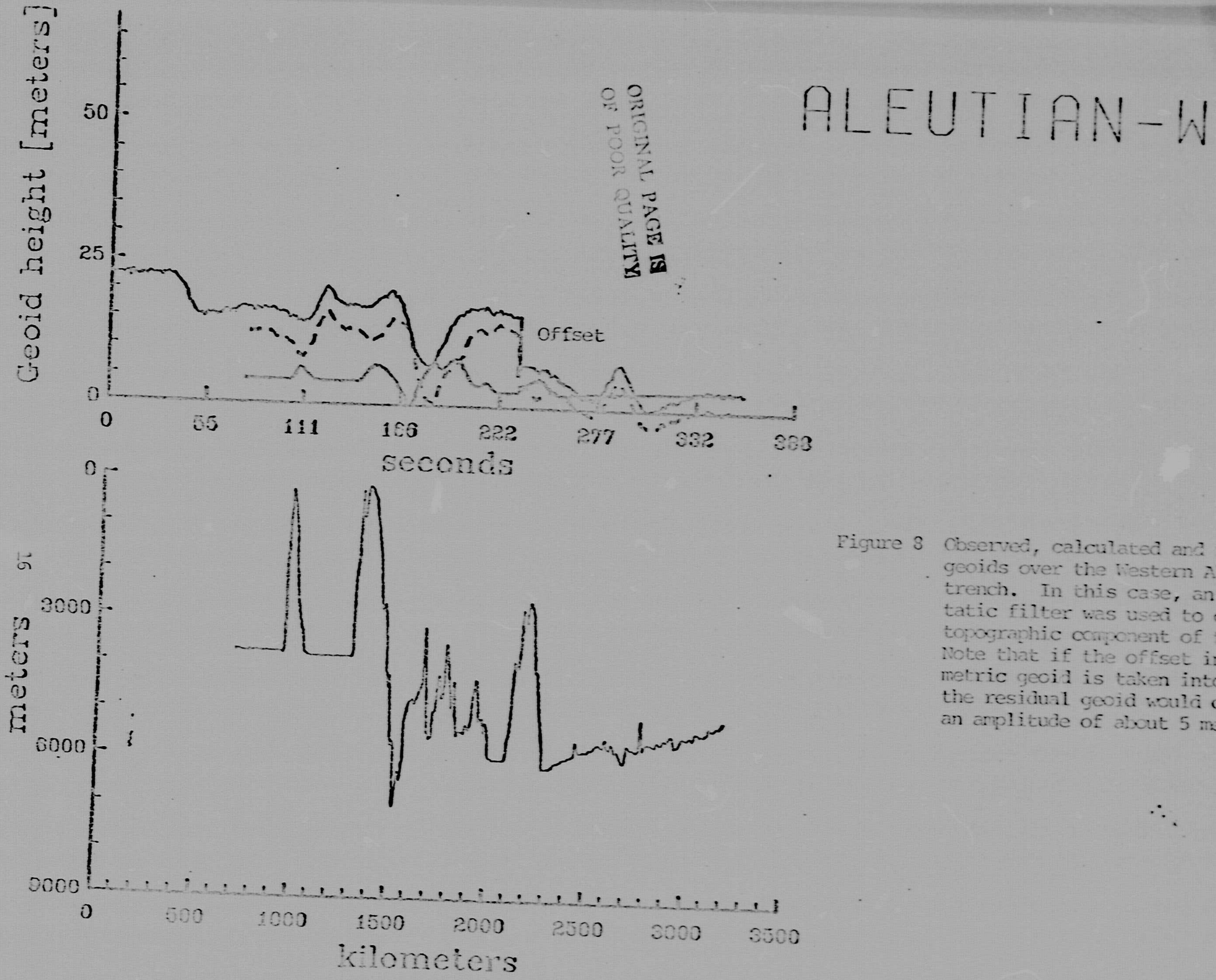

Figure 8 Observed, calculated and residual geoids over the Western Aleutian trench. In this case, an Airy isostatic filter was used to compute the topographic component of the geoid. Note that if the offset in the altimetric geoid is taken into account, the residual geoid would only have an amplitude of about 5 meters.

1. Further analysis of altimeter data

It is proposed to extend the method described about to other trench island arc systems in order to look for any systematic patterns in residual geoid anomalies and also to compile a catalog of residual geoid profiles for use in testing the numerical models described below.

A related line of research will be to develop methods of using 3-dimensional isostatic geoid filters. This will compliment work on the analysis of 2-D profiles and will also allow the isostatic and residual geoid anomalies to be calculated for specific regions of the world. It is planned to utilize an extensive data set of 1° x 1° bathymetry measurements and radar altimetry geoidal heights recently acquired from the National Geophysical and Solar-Terrestrial Data Center. Comparison of the 2-D and 3-D results along common lines should provide a useful test of the relative merits of each method. Regional maps of isostatic and residual geoid height variations will be published as a result of this work.

2. Development of numerical models of a subduction zone

Finite-difference models of the deep structure of seismic zones have been developed and further work in this area is required. The construction of these models has been guided by the following factors:

1. The models should be as consistent as possible with what is presently known about subduction zones without introducing a priori assumptions. For example, although the relative motion (and in some cases, the absolute motion) of the converging plates at the surface is reasonably well determined for most trenches, the attitude of the streamlines at depth is not. The common assumption that the planar Benioff zone defined by the foci of intermediate and deep earthquakes lies parallel to the surface of the descending lithosphere is only an assumption which is not subject to any rigorous test. It is largely based upon the conclusion of Isacks and Molnar (1971) that such an interpretation is consistent with the focal mechanisms of intermediate and deep earthquakes. However, Isacks and Molnar assumed that stresses within the descending plate were generated by forces applied to the ends of the plate. If these stresses are in fact caused by surface tractions due to the motion of the plate through the mantle, then the same focal mechanisms argue against the idea that streamlines are parallel to the Benioff Zone. Obviously, any satisfactory model of a subduction zone must produce stresses that are at least consistent with the focal mechanisms of deep earthquakes, but this should be a result of the model, not a primary input.

2. The models must be numerically tractable and the computing algorithm sufficiently fast that testing of a

wide range of parameters and boundary conditions is feasible.

A satisfactory compromise between these factors appears to have been achieved with the model that gave the results shown in Figure 9. The governing equations were solved using finite differences on a 25km grid within a rectangular box 2500km wide by 600km deep. The depth of the computing region can be increased once the numerical scheme is in final form. Upwind differencing was used to maintain numerical stability in the temperature equation. Factors included in the computations so far include adiabatic compression, variable thermal conductivity and internal heat sources. More complicated effects, such as internal buoyancy forces and shear strain heating have not yet been included since the rheology assumed so far is Newtonian and therefore unrealistic. Once problems with introducing a more realistic rheology have been solved, these additional factors can be considered.

The main difference between the model shown in Figure 9 and most other previous models lies in the boundary conditions. On the horizontal boundaries the conditions are that the vertical velocity is zero except in a 100km wide transition region on the upper boundary and that the horizontal velocities assume specified values. The specification of a non-zero horizontal velocity on the lower boundary allows the effects of trench migration with respect to the lower mantle to be investigated. On the vertical boundaries, the conditions are zero vertical velocity, and continuity of shear stress. Where material enters the region the temperature is specified. When it leaves the region, the horizontal tem-

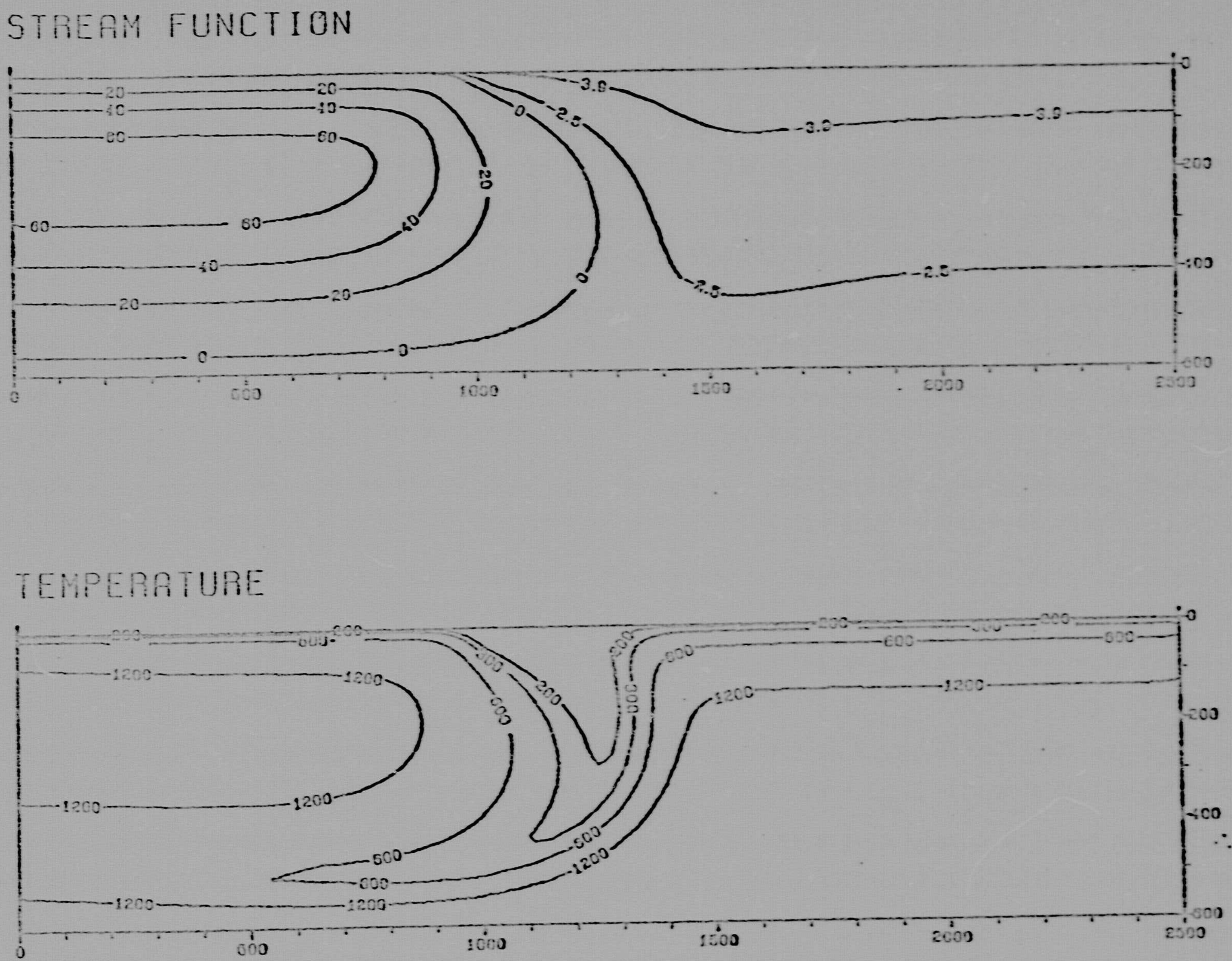

Figure 9 Flow and temperature in a subduction zone calculated using a constant Newtonian viscosity. The assumed rate of convergence on the upper boundary is 8 cm/year. Stream function values scaled by 10^6 cm^2/year. Isotherms in °C.

perature gradient is assumed to be zero. These conditions represent a smooth continuation between the flow and temperature inside and outside the region. In spite of the large number of grid points and the necessity to adjust the vorticity on the boundaries to satisfy the velocity conditions, the use of an Alternating Direction Implicit scheme produces rapid convergence.

Because of the uncertainty in the position of the slab at depth, no rigid boundary is specified within the interior of the region. The aim is to use a temperature- and pressure-dependent viscosity and allow the dynamics of the flow to determine a region of high viscosity that can identified as the downgoing slab. It is necessary, however, to simulate the initial attitude of the streamlines at the upper surface. This is done by introducing a 100km wide transition zone on the upper boundary within which the velocities vary smoothly from a value appropriate to the convergence velocity of the seaward plate to a zero value landward of the trench. The values of the stream function within the transition zone are calculated so as to be consistent with conservation of mass over a 5km thick region. Thus the upper boundary of the model represents a depth of 5km in the earth and the temperature values on the upper boundaries are adjusted accordingly.

Figure 9 shows that with a constant Newtonian viscosity the streamlines spread out beneath the trench leading to a broad zone of descending material . As a consequence, temperatures at depth are unrealistically low, since the zone of descending material is too thick to be heated up appreciably by the surrounding hot

mantle. In reality, it is to be expected that the zone of descending material will be much narrower because of the effects of temperature -dependent rheology.

The next step is to modify the rheology so as to take into account this effect. It is planned to use the most recent determination of the flow law of olivine (Ross et al, 1979) which includes a power law exponent and the experimentally-determined value of the activation volume for creep. The creep law has been cast in a tensor form so that the existing numerical method can be used, but with an additional term taking into account the variation of viscosity. It is well known that extreme variations in viscosity lead to numerical instability, so that it will be necessary in the computations to limit the range of effective viscosities allowed. Nevertheless, enough of a viscosity variation can be included to substantially alter the flow pattern shown in Figure 9 and hopefully lead to a narrow zone of descending material beneath the trench.

Some of the additional factors that will be included in later models are internal buoyancy forces, shear strain heating and the effects of phase changes. Quantities calculated from the models will include stresses within the flow for comparison with the inferred focal mechanisms of deep earthquakes; surface deformation; and the resulting shape of the geoid at the surface for comparison with the residual geoid obtained in the other part of the study.

Modifications to the boundary conditions will include extending the depth of the region to 1200km to look at the effect

of a deeper return flow and also prescribing a non-zero horizontal velocity on the lower boundary. The latter modification is in order to simulate the effect of migration of the trench with respect to the deep mantle which has not been included in any previous work.

Although the model proposed above is fairly complicated, it is tractable provided that care is taken to ensure numerical stability, and promises to offer some new insights into our understanding of processes occurring in subduction zones. Using the results of this study, it may be possible to address some of the outstanding questions related to the role of subduction zones in driving plate motions.

Proposed Timetable

Funds are requested in this proposal for a two-year study of this problem. During the first year, efforts will be concentrated on:

(1) Extending the calculation of two-dimensional isostatic geoid anomalies to all the major trench/island-arc systems of the world;

(2) Developing methods for applying three-dimensional geoid filters; and

(3) Extending the numerical model to handle non-linear temperature- and pressure- dependent viscosity.

Parts (1) and (2) of this study will be initiated in September, 1980, and supported under NASA grant NAG 5-94 "Altimetry Data over Trenches and Island Arcs and Convection in the Mantle" during the period 9/1/80 - 1/31/81.

The second year of the study will be devoted to comparing the results of the models with observational data and looking at the effects of additional factors that may be important in governing the flow patterns and temperature in subduction zones.

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BIOGRAPHICAL DATA

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	1969-1971	Engineering Seismologist, John V. Dinan Associates, Fort Lee, New Jersey
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	1977	Secretary for Gravity Section of the National Aeronautics and Space Administration's Earth Dynamics Summer Workshop, Boulder, Colorado, July 18-23.

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